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Performance analysis of a Gamma type Stirling engine using three different solar concentrators

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ABSTRACT

This paper reports the performance characteristics of a gamma type Stirling engine using three different types of solar concentrators i.e. a Fresnel lens, a parabolic concentrator with aluminium foil having an array of mirrors pasted on it assembled with a double convex lens at its focal point and the third one, the same parabolic concentrator attached with a Fresnel lens in replace of a double convex lens at its focal point. Out of the three concentrators, the best possible results were obtained from the Fresnel lens attached to the parabolic concentrator with aluminium foil having temperature range between 80 – 95 °C. The maximum torque is 1.52 Nm obtained using Fresnel lens attached at the focal point of a parabolic concentrator with aluminium foil having an array of mirrors at 181 rpm and maximum shaft power is 35.16 Watt at 280 rpm.

Keywords: Gamma type Stirling engine, Fresnel lens, parabolic concentrator, mirror, Double convex lens

1. INTRODUCTION

Presently, world's energy demand is replenished by fossil fuel. That's the cause behind the rapid depletion in the fossil fuels and degradation of the environmental conditions. This is the reason behind the interest and focus on alternative energy sources as well as different effective conversion systems are also developed. Stirling engines are a type of external combustion engine or heat engine, which can be effectively utilized for the conversion of the heat energy or the solar energy to mechanical energy, and further this mechanical energy can be converted to electricity [1].
As Stirling engines are external heat engines, so heat from any source can be effectively utilized to run the engines. Heat from the fossil fuels, waste heat from industry, heat produced by combustion of combustible elements, waste heat from thermal power plants, heat from radioisotopes and even the heat energy from incident solar radiation can also be used to run this engine. In recent condition, the whole world is in the need of a green energy technology; in this aspect, a Stirling engine driven by heat using solar radiation as source can be effectively contribute [2]. For this application, the Low Temperature Differential Stirling engines will be the best choice [3]; gamma type Stirling engines are such type of Stirling engines [4].
Different heat inputs can be implemented like domestic gas burner, even radio isotopes can also be used to create a Stirling radioisotope generator. However, utilizing these heat sources will create environmental pollution and environmental hazard to different extents. Solar driven Stirling engine is a green energy technique. The solar driven Stirling system requires proper concentrator to concentrate or focus the solar radiations to a specific point where higher temperature will be generated. The hot end of the Stirling engine can be placed at the focal point of the concentrator and this concentrated solar radiation will be the heat source of the engine [5].
Some of the most commonly known Concentrators or collectors are Parabolic Dish reflector, Fresnel lens, parabolic trough type collector, etc [6]. Parabolic Dish Concentrators are point focus concentrators [7]. These types of reflectors concentrate solar irradiation to the focal point of the dish. The structure of the dish and overall mounting arrangement should have provision for the dish to track the sun fully. At the focal point, the temperature is considerably high to drive a Gamma type Low Temperature Differential Stirling engine. A Fresnel lens is a special type of lens with a large aperture and a short focal length with less material as compared to conventional lenses. This type of lens can capture comparatively more oblique light from the light source. These lenses can be effectively used in solar applications; already used in solar cookers and as solar collectors [8].
Fresnel lenses are also utilized to concentrate solar energy to the solar cells. These lenses can be effectively used as a heat source for a gamma type Low Temperature Differential Stirling engine. Parabolic Trough collector is made of sheets of reflecting materials into a parabolic shape. Generally a receiver tube is placed on the focal line of the trough type collector. When the concentrator is pointed toward the sun, the incident rays get concentrated on the focal line.

The temperature generated on the receiver tube is sufficient to run a Low Temperature Differential Stirling engine. There are different green energy methods implemented and some of them are under development, the energy generated by utilizing the non-conventional sources are called green energy techniques, as they involve less harmful emissions and effects. Solar energy is the largest source of energy in the world. Successful implementation of such solar-based green energy systems is very much desirable in recent days. Implementation of a Stirling engine with a proper solar concentrator can be proven as an effective way to generate electricity with negligible environmental impact.

2. EXPERIMENTAL FACILITIES

In this performance test, a gamma type Stirling engine was used with no regenerator. The hot end displacer cylinder of the engine is made up of stainless steel while the power cylinder is made up of brass. Since, the power piston has to slide in the power cylinder and has to prevent air leakage as well; hence the power cylinder is made up of brass. Both the power piston and the displacer cylinder are made of aluminium. Brass bushing is provided at the displacer piston rod to prevent leakage from the displacer cylinder. The flywheel is made up of aluminium [9]. The table below shown the specifications of the engine used for testing purpose.

Table 1: Technical Specifications of Engine

Parameters	Specification	
Engine type	Gamma type Stirling engine	
Displacer piston	Bore x stroke (mm)	32 x 20
	Swept volume (cc)	16.07
	Material	Aluminium
Power piston	Bore x stroke (mm)	20 x 20
	Swept volume (cc)	6.28
	Material	Aluminium
Power cylinder	Material	Brass
Displacer cylinder	Material	Stainless Steel
Working fluid	Air	
Cooling system	Water Cooled	

The first test was conducted with a Fresnel lens with dimension 245 x 170 mm has a 3x magnification factor used for the analysis on the hot end of displacer cylinder of gamma type Stirling engine. The Fresnel lens is used as a solar concentrator for our analysis and different temperatures were measured using the thermocouple MASTECH MS6550B with an accuracy of 0.1 ° C [10].

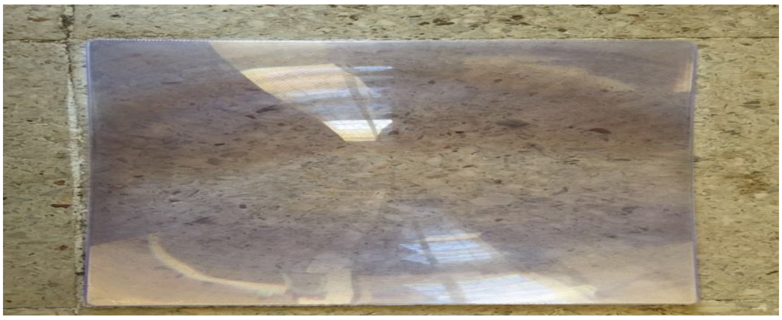

Figure 1 Fresnel lens

The second test was done using a parabolic concentrator with aluminium foil having an array of mirrors pasted on it & assembled with a double convex lens at its focal point. There is a provision made to hold the double convex lens above the parabolic concentrator so that the focal point can be made over the hot end of the displacer cylinder. A double convex lens has an aperture diameter of 240 mm and focal length of 150 mm was used. An aluminium foil of 0.3 x 2 m dimension, having a reflectivity of 0.87 was used over a parabolic shape structure made up of tin with a coating over it. An array of mirrors, in which each mirror has a dimension of 2 x 2 inch, having a reflectivity of 0.97 are placed and pasted over the parabolic concentrator. The whole lens setup was assembled over the concentrator. Different readings were obtained at different temperatures using the same thermocouple [11].

Figure 2 Parabolic concentrator

The final test was done using the same parabolic concentrator replacing the double convex lens with the Fresnel lens. Provision was made in the same way for assembling the Fresnel lens at the focal point of the parabolic concentrator. The use of Fresnel lens firstly provides an approximate point focus on the hot end of the displacer cylinder and secondly, it increases the heat intensity at its final focal point.

Figure 3 Double convex lens

A brake dynamometer with a strain gauge load sensor was used to measure the torque of the engine with an accuracy of 0.01 Nm. The pressure inside the displacer cylinder was measured by means of a Bourdon tube pressure gauge mounted on the end of displacer cylinder. A digital tachometer, DT-2234C with 1 rpm accuracy was used to measure the engine speed during its performance tests. The hot end temperature of displacer cylinder was measured by a thermocouple attached to its hot end. Temperatures were measured with a MASTECH MS6550B, a laser target pointer with a temperature resolution of 0.1 ° C, which can measure up to 650 ° C. The solar energy density was measured using WACO 206 pyranometer for the given capture area of the respective concentrator [12, 13].

Figure 4 The test Stirling engine

3. RESULTS AND DISCUSSION

Initial, the engine set up included only Fresnel lens assembled to it and allowed it to focus on the hot end of the displacer cylinder. The results obtained for hot end temperature versus engine speed, engine speed versus torque and engine speed versus shaft power were plotted in figure 5 & 6. The test was conducted for a steady solar energy density value of 910 W/m^2. For the Fresnel lens capture area 0.042 m^2, the incident solar energy was calculated to be 38.22 W. From the hot end temperature versus engine speed plot, 250 rpm was the highest speed obtained at 88 ^{o}C. At 2 bar pressure, 32.4 W was the maximum shaft power obtained at an engine speed of 250 rpm which speed was not the same for maximum torque. From the plot, the maximum torque of 1.37 Nm was obtained at a speed of 175 rpm.

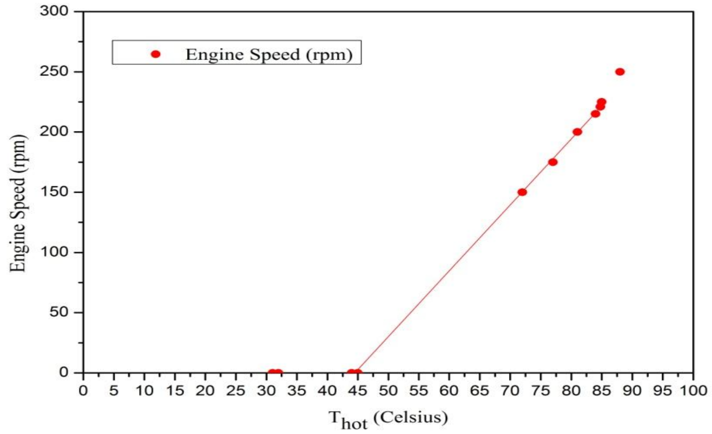

Figure 5 Hot end temperature vs engine speed using Fresnel lens.

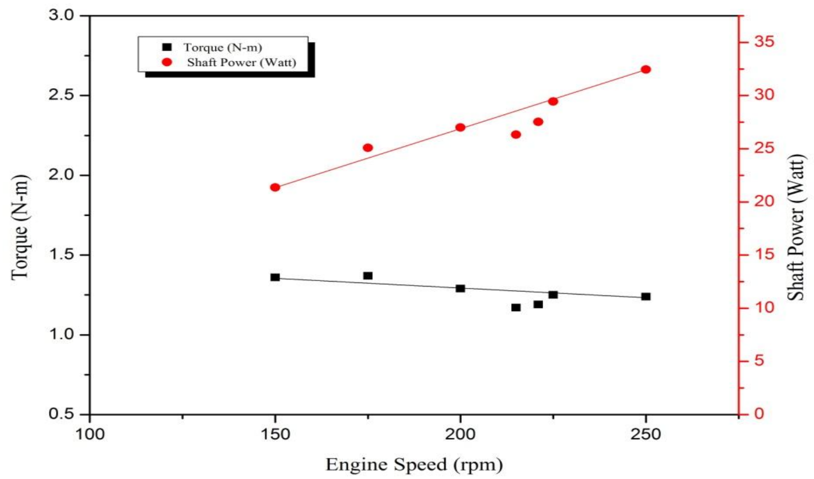

Figure 6 Engine speed vs torque and shaft power using Fresnel lens.

The second engine test was done using a parabolic concentrator foiled with aluminium and mirrors pasted on its surface so as to increase its reflectivity. Since the focal area was large compared to the size of the hot end of the displacer cylinder, a double convex lens was used at the focal area of the parabolic concentrator. It helped to concentrate the radiations from the parabolic concentrator on the hot end of the displacer cylinder. The solar energy density at steady state was calculated to be 920 W/m^2. This resulted to 41.59 W of incident solar energy for 0.045 m^2 of double convex lens capture area. The values of engine speed for different hot end temperature were noted and plotted. 252 rpm was the maximum engine speed corresponding to 88 ^{o} C temperature. From the plot of engine speed versus torque and engine speed versus shaft power, the maximum shaft power of 33.7 W was obtained at an engine speed of 252 rpm where as the maximum torque of 1.47 Nm was obtained at an engine speed of 155 rpm. . The results obtained for hot end temperature versus engine speed, engine speed versus torque and engine speed versus shaft power were plotted in figure 7 & 8.

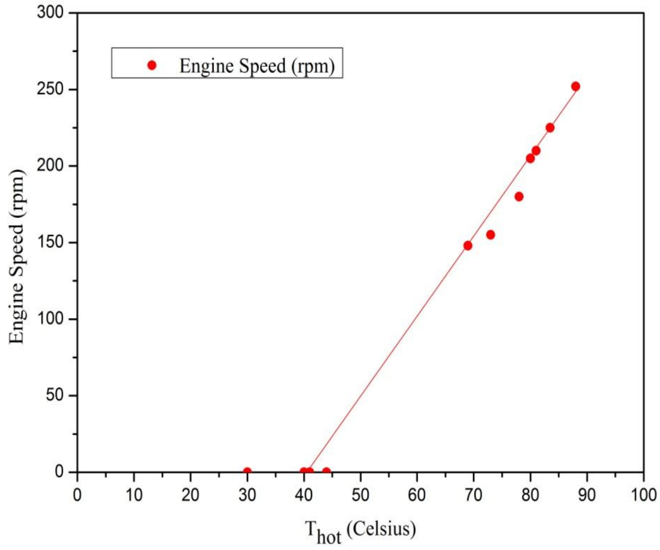

Figure 7 Hot end temperature vs engine speed using parabolic concentrator with double convex lens.

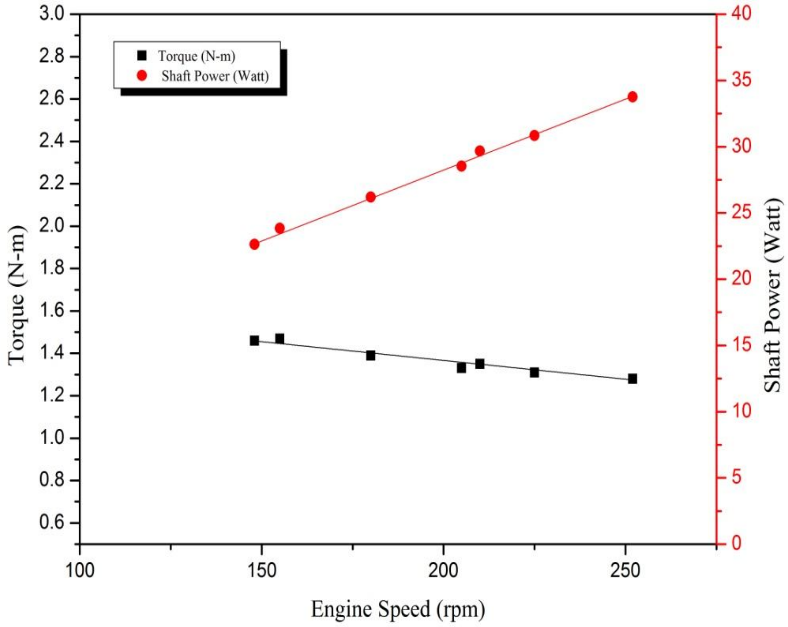

Figure 8 Engine speed vs torque and shaft power using parabolic concentrator with double convex lens.

The third and final test was done using the combination of the same parabolic concentrator and the Fresnel lens of same capture area. The Fresnel lens was positioned similarly at the focal area of the parabolic concentrator which further concentrated the solar radiations on to the hot end of the displacer cylinder. The solar energy incident was 38.11 W for the same capture area of the concentrator with the solar energy density value of 915 W/m^2 at steady state. Engine speed versus hot end temperature plot showed that the maximum speed of 280 rpm was obtained at 95 ^{o}C. From the plot of engine speed versus torque and engine speed versus shaft power, it was observed that the maximum torque of 1.52 Nm and maximum shaft power of 35.16 W was obtained at 280 rpm and 181 rpm respectively. . The results obtained for hot end temperature versus engine speed, engine speed versus torque and engine speed versus shaft power were plotted in figure 9 & 10.

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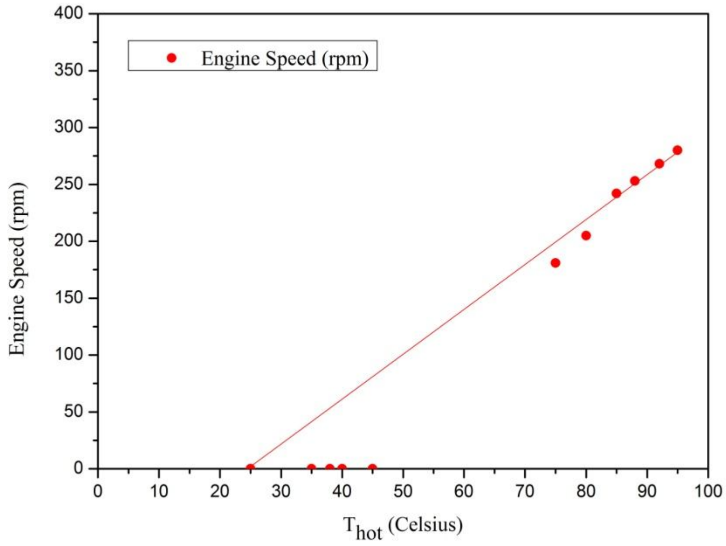

Figure 9 Hot end temperature vs engine speed using parabolic concentrator with Fresnel lens.

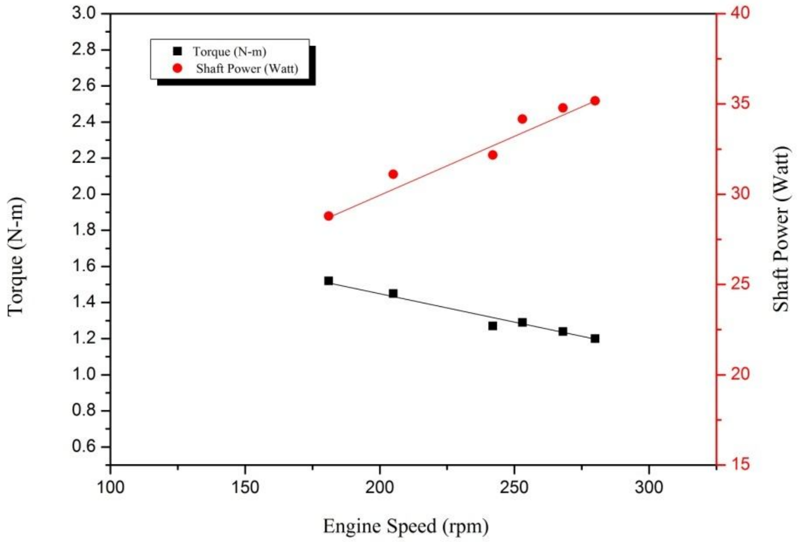

Figure 10 Engine speed vs torque and shaft power using parabolic concentrator with Fresnel lens.

From all the plots obtained, it was observed that they all differed from each other for all three engine tests performed using Fresnel lens, parabolic concentrator with a double convex lens and the same parabolic concentrator with Fresnel lens. It was also observed that for all the three tests performed, none gave the maximum torque and maximum shaft power at same engine speed.

4. CONCLUSION

The paper presented the performance characteristics of a gamma type Stirling engine using three different concentrators. The parabolic concentrator with aluminium foil on which mirrors were pasted on, has a Fresnel lens attached to its focal point was used to measure and analyze the readings with other two concentrators for the engine characteristics. The maximum torque is 1.2 Nm and maximum shaft power is 35.16 Watt was obtained at 280 rpm when the temperature of the hot end of the displacer cylinder was 95 ° C and was focused by using parabolic concentrator, with a Fresnel lens attached to its focal point. Below the specified temperature of the hot end of displacer cylinder for all the concentrators used, the speed was decreased gradually which resulted in more vibration and this made the engine to stop.

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